Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Renewable and Sustainable Energy Reviews 13 (2009) 216–222
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

The key technology of offshore wind farm and its new development in China

Wang Zhixin, Jiang Chuanwen*, Ai Qian, Wang Chengmin

Department of Electrical Engineering, Shanghai Jiaotong University, 800 Dongchuan Road, Shanghai 200240, PR China

Received 15 June 2007; accepted 6 July 2007

Abstract

The paper reviews characteristics and the developing state of abroad offshore wind farm briefly, and the key technology related to offshore wind farm. The optimization configuration and assessment of abroad offshore wind farm, and rational distribution assess, offshore wind farm electric transmission technology, system insert with operating, wind farm MES and wind turbine base, etc., are studied to put forward corresponding implementation and solution. The conditions for research and development, and demonstration of its application are suggested. Through studying key offshore wind farm technology, we can make offshore wind farm system optimization designing techniques reach the most advanced levels internationally, train teams with innovation ability, which are engaged in designing and running wind farm to manage wind-power electricity generation and wind farm design . All of these are of strategic, economic, social and academic value.

Keywords: Offshore wind farm; Electric transmission technology; Wind turbine base; Energy quality; Wind farm manufacturing execution system

Contents

1. Introduction of the research and construction of offshore wind farm

The first offshore wind generating international conference and exhibition was held in Copenhagen from October 26 to 28 in 2005. Wind power issues, such as, policy, marketing and technology were discussed during

*Corresponding author. Tel.: +86 21 34205930; fax: +86 21 54747501.
E-mail addresses: wangzxin@sjtu.edu.cn (W. Zhixin), jiangcw@sjtu.edu.cn (J. Chuanwen).

1364-0321/$ - see front matter
doi:10.1016/j.rser.2007.07.004

the meeting. The Copenhagen strategy on offshore wind power development was also proposed by some European energy officials, in which offshore wind power was deemed an important means to ensure the objective of a renewable energy account of 21% of all energy by 2010. Meanwhile, proposals for action to develop the offshore wind power market, to obtain access to the power network and the impact of these on the environment were discussed. Offshore wind power generation has become an important direction in the area of wind electricity generation. Denmark has become the world's center of offshore wind power. Unit capacity achieved is 5 MW for commercial operations at present, and the scale of grid-connected wind farming is constantly expanding. Large wind farms are developing from land to coastal waters because of the rich wind marine resources, scarcely occupied land, and minor environmental constraints. And wind energy can be more fully utilized in offshore wind farm, which yield 20–40% higher energy revenue compared with land wind turbines, for the high speed of coastal waters, low turbulent intensity and large power generation. Generating cost of offshore wind farm is related to economy of scale, for example, unit capacity of offshore wind unit and the total units per wind farm. Laying down 150 MW submarine cables is similar to 100 MW. Mass production of units and steel structure is beneficial to decreasing cost. The optimal scale for offshore wind farm is 120–150 MW.

Offshore wind farm is constructed in general on the continental shelf area which is about 10 km away from the coast and 10 m deep. Compared with land, offshore wind turbines must be fixed on the seabed, which demand a more solid supporting structure. Submarine cables are needed for transmission of electricity, and special vessels and equipments are required for building and maintenance work. These factors create high costs, with double or triple the cost in land. Offshore wind farm has a number of advantages, such as avoiding land-use disputes, no special requirement for geology, high wind speed, rich wind energy, etc. The average unit capacity is about 3 MW, the largest has up to 5 MW. The average annual utilization hours is about 3000 h, some go up to 4000 h.

Compared with land wind farms, offshore environment provides a number of opportunities, but imposes a number of constraints. It needs more complicated prior construction work for setting up 70 m, even 100 m wind measurement tower. It needs field observation on the movement of the seabed topography and other basic geological conditions. It needs consideration of wave and wind load at the same time and higher structural strength support requirements. The use of large turbines demands more complicated manufacturing technology and more rigid erosion protection. Bad weather and long distances to the shore increase operation and maintenance costs and can decrease availability for the unique environment.

Conducting research and development of offshore wind power began in the seventies of the last century and is mainly concentrated in Europe and the United States. It can be roughly divided into 5 periods. These are national research on resources and technologies of offshore wind farms in Europe (1977–1988), European-class offshore wind farm research, which began to implement a number of demonstration projects (1990–1998), medium-sized offshore wind farm (1991–1998), development of large-scale wind farm and large-scale offshore wind turbine (1999–2005) and large-scale offshore wind farm (2005–). After more than 30 years of development, offshore wind power technology is becoming more and more mature and has entered the stage of large-scale development.

Offshore wind power has attracted attention around the world, and the development of offshore wind power development is to argue for a direction. At present, offshore wind power technology has become more and more mature and has entered the large-scale development phase. Total accumulated capacity of offshore wind power is almost 800 MW (see Table 1) compared with over 900 MW offshore wind power, the deadline for the end of 2006 . Denmark, Britain, Ireland, Sweden and the Netherlands and other countries are developing offshore wind power fast. In the 20th century and the early 1990s, Denmark began to try wind power at sea. The world's first offshore wind farm was built in 1991. The Danish government's tender to build in 2 blocks of the sea about 16 MW of wind power demonstration was projected in 1997. And now they have been put into operation. Nysted wind farm on the south coast was built to be the biggest offshore wind farm in 2003, which has a capacity of 165.6 MW composed of 72 × 2.3 MW Taiwan Bonus units. It began generating electricity in December 2003. Approved by the Danish Parliament, the Danish energy authority has planned to develop two offshore wind farms located in Horns Rev and Rodsand, respectively, in 2004. There is a plan to build a 20 MW offshore wind farm in 2006. According to article 21 of the Danish government's energy bill, installed capacity at sea will reach 400 MW before 2030 and added to 1500 MW on land, wind power generation will enable Denmark to provide one half of its electricity; the German government aims to reach an installed offshore wind power capacity of 3000 MW in 2010, and 23 GW by 2030; Holland's goal is to have a capacity of 275 MW of wind power in 2020, with 125 MW installed in the North Sea continental shelf region; Sweden aims at 3300 MW up to 2019; the Plan of Europe is to reach an installed capacity of 240 000 MW and an annual output of 720TWh up to 2020, which will meet one-third of the consumption demand in Europe. European Wind Energy Association predicted that the development of offshore wind power will become an important direction of wind power during the next 15 years. It is expected that in 2010 and 2020. European offshore wind power capacity will reach 10 million and a total of 7000 MW. Green Peace Organization prospects a more optimistic estimate to the European offshore wind power development. It is expected that in 2020, the European offshore wind power capacity

Table 1
Global installed capacity of offshore wind farm

No.	Country	Year	Unit type	Number	Accumulated capacity(MW)
1	Denmark	1991	Bonus-450 kW	11	409.9
		1995	VestasV39-500 kW	10	
		2000	Bonus 2 MW	20	
		2002	Vestas V80-2.0 MW	80	
		2003	Bonus 2.3 MW	72	
		2004	Bonus 2.3 MW, Vestas V90-3.0 MW, Nordex N90-3.0 MW	1 + 2 + 1	
2	UK	2000	Vestas V66-2.0 MW	2	314
		2003	Vestas V80-2.0 MW	30	
		2004	Vestas V80-2.0 MW	30	
		2005	Vestas V90-3.0 MW	30	
		2006	Vestas V90-3.0 MW	30	
			Repower 5 MW	2	
3	Ireland	2003	GE Wind 3.6 MW	7	25.2
4	Sweden	1997	Wind World 550 kW	5	23.3
		2000	Enron 1.5 MW	7	
		2001	NEG Micon 2 MW	5	
5	The Netherlands	1994	Ned Wind 500 kW	4	18.8
		1996	Nordtank 600 kW	28	
6	Germany	2004	Enercon E112	1	7
			NordexN80	1	
Total					798.2

could reach 240 million kW, and will meet one-third of the electricity demand of Europe [1–4].

In recent years, some provinces in China have started preliminary construction work for offshore wind farm. The successful construction of Shanghai Donghai Bridge offshore wind farm, which will be finished in 2009, with installed 100 MW wind turbines, provides a series of advantages, such as master of evaluation on offshore wind energy, design and construction technology etc. Meanwhile, research is developed combined with national research projects. A technical standard system is gradually established and design and manufacture technologies which owns independent intellectual property rights is formed. These create conditions for development scale. It is planned to establish offshore wind farm with 1000 MW in Zhejiang Province and Jiangsu Province, China. Four offshore wind farm issues listed in Table 2 sets out the national technology support program in 2006, which develops the research on building technology problems and detection platform and technical standards.

2. Key technologies of offshore wind farm [6–12]

Table 3 focuses on the key technologies of offshore wind farm [5].

Macro- and micro-siting are included in offshore wind farm site location options. Offshore wind farm plan is based on assessment, research on location, wind energy resources and considerations of power demand, and grid-connection and system conditions, such as geology, geomorphology, the fairways and fishing. During the development, it is particularly important in the early wind resources evaluation. So far, Riso WASP is widely used.

Table 2
Offshore wind power issues supported by National Science and Technology Program in 2006

Project name	Major research contents
Key technologies of offshore wind farm construction	Research on foundations of units, basic strength design, Testing and evaluation of technical infrastructure damage, site selection, electrical transmission, and selection, installation, operation and maintenance technology of wind turbines.
M&O of offshore wind turbines	Research on special installation and maintenance of farm, and construction technologies.
Technology, economic analysis and evaluation on influence of environment	Technological and economic analysis on the construction of offshore wind farm and evaluation on environmental impact of offshore wind farm.
Building technical manuals	Research on site selection, foundations, unit design technology etc.

It has been focused on the model of penetration power calculation, while there is little research on the considerations of grid structure, load levels and access methods.

3. Development of offshore wind farm key technologies

3.1. *Optimal configuration and evaluation of offshore wind farm*

Wind speed combination forecasting model is constructed using data mining technology and intelligent clustering technology and a variety of forecasting methods. Based on power generation forecasting and research on

Table 3
Key technologies of offshore wind farm

Key technologies	Contents and characteristics
1. Foundations	1. Bearing hydrodynamic and aerodynamic load, considering factors as wind and wave load, support construction and dynamic characteristics of wind turbines and response to unit control system etc. 2. Types of foundations: (1) gravity, mature construction and installation technologies, suitable for water depths about 0–10 m. The disadvantages are seabed needed and hard to remove with large weight and size; (2) mono pile foundation, no need of seabed preparation, simple to manufacture, be considered for depth of 0–30 m. The disadvantage is special installation equipment is needed. (3) tripod foundation, seabed preparation is little needed, suitable to water depths higher than 20 m. 3. IEC61400-3 based
2. Selection of site	Considered factors: (1) wind resources; (2) permission to project construction; (3) rights of using farm site; (4) grid situations, location and voltage levels of transformer station, accessible largest capacity and grid plan, etc.; (5) sites situations, scope, water depths, wind resources and marine geological conditions; (6) environment constraints. Negative impact on tourism, birds, fishing and coast defense.
3. Wind measurement	(1) Primary evaluation of wind resources: evaluate power generation through weather station, oil drilling platform, etc. (2) Installing wind measure tower about 50–80 m or beacon wind measurement. In addition, Ultrasonic radar wind measurement instrument can also be adopted. Its character is that the installation is under the low plane and measurement is on the flow platform.
4. Investigation	(1) Sonar is used to survey sites, water depths, and drawing water depths maps. These provide basis for microsite and design of outlines; (2) collecting soil data of surface layer; (3) seabed exploration drilling depth is 20–40 m under sea geological conditions. (4) Measured waves, tides and currents and other data used to calculate the foundation of hydrodynamic loads of underwater structures.
5. Wind turbines of offshore wind farm	(1) Greater diameter and lower rated speed of the same rated power generating units; (2) the little rate of change of wind speed with the variable height; (3) the speed of units increase by 10–30%. Power generation is increased and torque is decreased as well as decreased weight and cost of system; (4) corrosion protection standards are enhanced, such as internal closed measurement. In addition, dehumidification equipment is installed in the cockpit and tower; (5) new structures are used, which include double-blades, down wind direction, high-voltage transmission, etc.
6. Hoisting	Slifting vessels currently used are mainly modified boats. A2SEA modified ship, mayflower ship , jump-firecrackers are in operation. Among them, mayflower ship is constructed by Shanghaiguan shipyard. It has 6 extendable stents and 35 m operation deep, and can be installed at the base without assistance. Moreover, the whole lifting and installation method has been adopted.
7. Electrical transmission technology	(1) Offshore wind turbines are arranged in a certain way with the information of an independent group series connected with booster substations. Silicon resin cooling transformer is specially developed with good sealing property. (2) HVDC is used to decrease network loss and improve power quality.
8. Access and stability operation of system	Network access and grid-connection technology of offshore wind farm, which includes stability of grid, reliability and control strategy.

power system scheduling of the optimal operation problem, with real data obtained from wind farm and digital meteorological data, combing topography and unit arrangement, multiple-time-scale forecasting can be reported which include the next-day and day forecasting methods. These methods provide the basis for performing planned scheduling.

3.2. Electrical transmission and grid-connection

It is important to optimize grid-connected technology of wind farm, which ensures economical rationality. The first commercial offshore wind farm in Denmark is located in the marine 15–40 km away from the coast. And the installed capacity is between 120 and 150 MW. Offshore wind farm is connected to the backbone network by laying submarine cables. To reduce the risk of being damaged by the fishing tools, anchors, etc., cables must be buried. Submarine cables can be implanted in the seabed after the sea-bed is washed by high pressure water jets. This way is the most economical. Offshore wind farm can be connected to 30–33 KV voltage levels. Each wind farm has a platform of 30–150 KV transformer substation and many maintenance equipment. For the backbone network, grid-connection is controlled with generators based on HVDC technology. For different offshore wind farms, unit operation mode and voltage levels of grid-connection are determined by steady-state analysis and transient analysis. Optimal power flow model is determined based on the research of dynamic optimal power flow. The concerns of power quality, such as voltage fluctuation, flicker and harmonic, reactive control and voltage control, etc., can be used to improve the grid-connected quality.

3.3. Access and stability operation of offshore wind farm

Voltage stability of grid-connected operation is small disturbance voltage stability. It is mostly considered a static problem, and the *P–V* and *Q–V* curve methods which are based on power flow analysis are adopted. Compared with the fixed-speed wind turbine, variable-speed constant-frequency wind turbine is beneficial in improving the stability of the power grid. It will ensure voltage stability and reliability of wind farm on the research of reactive

power, voltage adjustment and frequency control strategy, which will improve the success ratio of grid-connection and ability of crossing fault.

3.4. Research and development of offshore wind farm MES

MES realized power system scheduling and operation, offshore monitoring system, equipment management and unit monitoring system, etc.

3.5. Foundations of wind turbines

(1) Traditional concrete foundation

As the name indicates, the gravity foundation relies on gravity to keep the turbine in an upright position. Vindeby offshore wind farm and Tunoe Knob wind farm are examples of this traditional foundation technique. The caisson foundations were built in dry dock near the sites using reinforced concrete and were floated to their final destination before being filled with sand and gravel to achieve the necessary weight. The principle is thus much like that of traditional bridge building. The foundations used at these two sites are conical which act as breakers for pack ice. Using traditional concrete foundation techniques the cost of the completed foundation is approximately proportional with the water depth squared the quadratic rule. The water depths at Vindeby and Tunoe Knob vary from 2.5 to 7.5 m. This implies that each concrete foundation has an average weight of some 1050 MT. According to the quadratic rule the concrete platforms tend to become prohibitively heavy and expensive to install at water depths above 10 m.

(2) Gravity + Steel foundation

Most of the existing offshore wind parks use gravitation foundations. A new technology offers a similar method to that of the concrete gravity caisson. Instead of reinforced concrete it uses a cylindrical steel tube placed on a flat steel box on the seabed. The advantage of this type is that the foundation has mature construction and installation technology. The disadvantage is that it needs seabed preparation and is hard to be remove because of its large weight and size.

(3) Monopile foundation

The foundation consists of a steel pile with a diameter between 3.5 and 4.5 m. The pile is driven some 10–20 m into the seabed depending on the type of underground. The monopile foundation effectively extends the turbine tower under water and into the seabed. An important advantage of this foundation is that no preparations of the seabed are necessary. On the other hand, it requires heavy duty piling equipment, and the foundation-type is not suitable for locations with many large boulders in the seabed. If a large boulder is encountered during piling, it is possible to drill down to the boulder and blast it with explosives.

(4) Tripod foundation

The tripod foundation draws on the experiences with lightweight and cost efficient three-legged steel jackets for marginal offshore fields in the oil industry. From a steel pile below the turbine tower emanates a steel frame, which transfers the forces from the tower into three steel piles. The three piles are driven 10–20 m into the seabed depending on soil conditions and ice loads. The advantage of the three-legged model is that it is suitable for larger water depths. At the same time only a minimum of preparations are required at the site before installation. This type of foundation is suitable at water depths higher than 20 m.

(5) The seabed is between 20 and 100 m, the floating offshore wind turbines are adopted, three or more wind turbines are linked together. So the cost of wind turbine foundation is largely reduced [13].

4. Wind energy generation of Shanghai, and development and basis of offshore wind farm technology

Shanghai has a lack of primary energy. The main primary energies of coal, oil, natural gas are all dependent on long-distance transportation and foreign imports which occupy a lot of capacity, terminals and yards. Shanghai has a large power demand, with installed capacity of 13 000 000 KW presently, while peak electricity attained was 19 000 000 KW in 2006, which requires scheduled power from other areas. Coal consumption is widely used in most of Shanghai's power plants, which account for 60% of energy consumption. This puts great pressure on environmental protection.

Shanghai, located in the western Pacific Ocean, is located at 31° north latitude, mid-latitude regions which is frequently subject to the south and the north wind. Being China's Yangtze River estuary, Shanghai's gate area is rich in wind energy resources in China. For its main wind direction is the southeast wind in summer, and the northwest or northeast wind in winter. The prevailing winds are mainly from the sea. This creates the ideal region for wind power development in the eastern coastal areas. Since 1997, 50, 70 m high wind measurement towers being constructed show average wind speed of 6.7 m/s at a height of 50 m. Effective wind power accumulated over time can achieve 7300 h. And equipment utilization hours can achieve 2000 h. At present, China has formed 4 grand banks with shoals areas of over 2000 km^2, where areas of 0 m above shoals are over 500 km^2. With the continuous deposition of these areas, new land can be used to develop wind energy. It is expected that in 2005, with the half utilization of these areas, total generation capacity can achieve 1500 MW of installed capacity and 30 billion kWh power generation on the evaluation of 6 MW per kilometer location. Since 2003, three wind farms have been constructed with the installed capacity of 1500 KW (GE), 1500 KW (GE), 850 KW (Gamesa). The total capacity

achieved is 24.4 MW. In the plan of Shanghai, wind power capacity objectives are 310 and 1000 MW, respectively [14,15].

Shanghai has a vast sea, and its development of offshore wind power generation has great potential. In 2006, the Shanghai Municipal Commission of Science and Technology set up a "mountain project" to focus on the research of key technologies of offshore wind resource utilization. This research aims at providing the basis for the utilization of rich offshore wind energy. Wind resources analysis, electrical plan, foundations and wind tower design are developed. Survey and Design Institute of Shanghai, Shanghai Electric survey and Design Institute, Tongji University and other research institutes are participating in the process.

Shanghai Electric Group Company and Shanghai FRP Research Institute sustain major projects of development and demonstration of wind power generating units, research on key technologies of offshore wind farm, and industrial development of blades with unit capacity larger than 1.5 MW. Shanghai Donghai Bridge 10 MW offshore wind farm has been the first to be established by the nation. The bid was won by the associated bid of the China Datang Group Corp, China Guangdong Nuclear Power Group-owned energy companies, China Power International Ltd and Shanghai Green Energy Ltd. The project will be completed in 2010.

Shanghai Donghai Bridge offshore wind farm with 100 MW plans to generate electricity in 2009. This project is different from a lot of offshore wind farms in Europe. The regional depth of water is about 8–10 m, the seabed under water is mainly thick silt which is 30 m, and silt quality soil layer, compares with that of wind farm abroad (with about 10 m of fine sand soil layer), the geological situation is quite unfavorable. The 4 m diameter single root foundation can be adopted abroad; meanwhile the 7 m diameter single root foundation is in China. In addition, laying the submarine cable of 6–10 km in the sea, around which global optical cable, electric power cable, navy optical cable , Sino-Japanese submarine cable ,etc., has increased the degree of difficulty enormously.

In 2007, a purpose for establishing a large floating offshore wind farm with 20 MW in Hainan Province, China, has been suggested, and wind turbine with vertical axis will adopted and installed 10 km away from the coastline.

5. Conclusion

(1) Associated with the economic improvement of our country, the load becomes greater and the quantity of energy consumption becomes larger. The critical circumstance of power supply shortage becomes worse, and it becomes the important limit of economy development. Energy saving, power efficiency improving, new type of power exploiting and using, multitypes of energy development, especially reproducible energy using, for example, the replaceable energy-wind energy, it obtains more attention by the government in the world and becomes one of the main energy source stratagems of country. The development of offshore wind generation must be related to economic movement, and strengthen the basal theory investigation, exploitation, demonstration and training.

(2) International wind energy market increasing at high speed. An 8 320 000 KW generator capacity was built in 2004 and 0.5% of it is wind generator capacity. The total generator capacity in 2006 is 30 GW, and may be 0.1231 billion in 2020, with 12% of it being wind generation.

(3) The first law of "reproducible energy resource" is legislated by NPC in 2005, and put into practice from January 1, 2006. The law advances the development of reproducible energy resource, and the wind energy becomes a new important strength except for thermoelectricity, hydroelectricity and nuclear power. The wind energy capacity increases quickly, it is the eighth in the world with 550 000 KW in 2003 and 1.26 million KW in 2005. It is the sixth in 2006 with 2.35 million KW. And it is expected to touch 5 million KW in 2010, 10 million KW in 2015, 30 million KW in 2020 (3% of country's generation capacity), 0.6 billion kWh (1.5% of generation quantity). All the generation capacity of wind farm in 2005 is 1266 000 KW, the generation of wind is 1864, it is increased 65.6% of 764 000 KW in 2004. The quantity of wind in trade is 15.3 hundred million, the 600 KW, 750 KW capacity of homemade generator is 28% of new capacity of generator, and the 72 % is produced by import generator. The rate of generator capacity of wind to total capacity is less than 1%, and 62 wind farms are distributed in 15 provinces (city, section or especially district). The development is fastest in Xinjiang, Neimenggu, Guangdong, Liaonin, and the capacity of these provinces is 48.5% of the country's wind energy capacity.

(4) To use wind energy scale and low cost,the key problem of high-power generator and offshore wind scale needs to be solved, to achieve the high efficiency reliability and low cost. The potential of wind energy, especially offshore wind energy, is vast. Wind energy will become the supplement of thermoelectricity. The conversion and deposit is aimed at the character of unstable, uncontrollable, non-storable and timely distribution and space. Scientific examinations are used to open out the rule and mechanism of capture, conversion and storage of wind energy, improve the operational reliability and maintenance, and achieve the conversion and storage with high efficiency, safety and reliablity.

(5) The key techniques of offshore wind farm includes optimization station and estimation, electric transmission and connection, system and stability operation, manufacturing excursion system(MES) investigation, and the base of wind generator, three connection

projects based on light HVDC generator disperse control. The researches of offshore wind farm are involved with system connection stability, reactive power and voltage control strategy, the interaction between wind farm and common nets. To satisfy and exploit conditions of large wind generation of deep-sea wind farm, resist typhoon and low temperature, a down-direction wind machine and "the group of offshore wind power generators with no fixed foundation" are used.

References

[1] Ying L, Hui G, Pengfei S. Current situation, technology, problem and outlook of offshore wind farm. Chin Wind Energy 2006(3):41–6 (in Chinese).

[2] Jie R. Wind power generation on sea- new trend of wind power. Global Look Technol Econ 2006(6) (in Chinese).

[3] 〈http://www.newenergy.org.cn/html/2006-2/2006213_7568.html〉.

[4] Hangye Y. Control technologies of wind turbines. Beijing: Mechanical Industry Publishing House; 2006.

[5] Zhixin W, Chengming W, Qian A, et al. Key technologies of optimal design of offshore wind farm system. Rep Chin Wind Energy Forum 2006;9 (in Chinese).

[6] Zhixin W, Chengmin W, Chuanwen J, et al. Key technologies of offshore wind farm. East China Electric Power 2007;35(2):37–40 (in Chinese).

[7] Li W, Zhixin W. Wind generator stabilization with DASM. In: Proceedings of IPEMC 2006, Shanghai, p. 520–5.

[8] Li W, Zhixin W. A basic study of fuzzy-logic-based power system stabilization with doubly-fed asynchronous machine. In: Proceedings of IPEMC 2006, Shanghai, p. 1492–6.

[9] Li W, Zhixin W, Tamura J. Smoothing control of wind farm output fluctuation with doubly-fed asynchronous machine. Proc IEEE PEDS Malaysia 2005:495–500.

[10] Li W, Zhixin W. Wind generator stabilization with doubly-fed asynchronous machine. WSEAS Trans Power Syst 2006;1(2): 12–6.

[11] Yun D, Zhixin W. Electro-hydraulic proportional control system of wind turbine pitch with variable speed and constant frequency. Mechatronics 2006;12(1):16–20 (in Chinese).

[12] Bin L, Zhixin W. Method analysis and simulation research on regulation of MW-class wind generator converter. J. Kunming Univ Sci Technol 2006;31(4B):21–5 (in Chinese).

[13] 荒川 忠一. 风力发电[J].日本机械学会会志 2006;109(1052):549–52 (in Japanese).

[14] Chuanyu H. It has great potential to develop wind power. Shanghai Energy Conserv 2006(3):17–21 (in Chinese).

[15] Jinhai H. Risk of first offshore wind farm in China. China Wind Energy 2007(1):73–4 (in Chinese).